

Thursday, July 30, 1998
CHONDRULES
8:30 a.m. Ussher Theatre

Chairs: R. D. Ash
J. S. Delaney

Alexander C. M. O'D.* Mock T. Carlson R.
Magnesium-Isotopic Fractionation in Tieschitz Chondrules

Delaney J. S.* Schnabel C. Herzog G. Flynn G.
Manganese-Magnesium-Iron and Manganese-Zinc Correlations in Magnesian Chondrules

Leshin L. A.* McKeegan K. D. Engrand C. Zanda B. Bourot-Denise M. Hewins R. H.
Oxygen-Isotopic Studies of Isolated and Chondrule Olivine from Renazzo and Allende

Leroux H.* Doukhan J. C. Libourel G. Perron C.
Metal-Silicate Differentiation During Chondrule Formation: An Analytical Transmission Electron Microscopy Study

Schneider D. M.* Akridge D. G. Sears D. W. G.
Size Distribution of Metal Grains and Chondrules in Enstatite Chondrites

Rubin A. E.* Sailer A. L.
Grain Size and the Abundance of Troilite and Moderately Volatile Elements in Low-Ferrous-Oxide Chondrules in Semarkona

Sanders I. S.*
Debris Clouds from the Earliest Planetary Impacts: Evidence from the Irish Meteorite Bovedy (L3)

Weidenschilling S. J.* Marzari F.
Did Jupiter Make Chondrules?

Genge M. J.*
The Ablation of Small Planetesimals: Yet Another Probable Chondrule Formation Mechanism

Grossman J. N.* Alexander C. M. O'D. Wang J. Zanda B. Bourot-Denise M. Hewins R. H. Yu Y.
The Lack of Potassium-Isotopic Fractionation in Bishunpur Chondrules

Georges P.* Libourel G. Deloule E.
Incorporation of Potassium in Molten Synthetic Chondrules Under Controlled Potassium and Oxygen Partial Pressures

Ash R. D.* Connolly H. C. Jr. Alexander C. M. O'D. MacPherson G. J. Rumble D. III
Oxygen-Isotopic Ratios of Natural and Synthetic Chondrules: Evidence for In Situ Reduction by Carbon

Tissandier L.* Libourel G. Toplis M. Chaussidon M.
Alkali Volatilization at High Temperature in Silicate Melts

Polnau E.* Eugster O. Krähenbühl U. Marti K.
Preexposure to Cosmic Rays of Chondrules

MAGNESIUM ISOTOPIC FRACTIONATION IN TIESCHITZ CHONDRULES. C. M. O'D. Alexander, T. Mock, and R. Carlson, Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Road, Washington DC, 20015, USA.

Background: Explanations for the diversity of chondrule compositions include: direct condensation [1], formation from heterogeneous precursors [2, 3], and evaporative loss [3]. Direct equilibrium condensation or formation from equilibrium condensate precursors should not result in large isotopic fractionations. Evaporation, on the other hand, can produce large isotopic fractionations if it occurs under Rayleigh conditions. As part of an effort to measure the isotopic compositions of a range of elements in UOC chondrules, we present new, high precision Mg isotope measurements of Tieschitz chondrules.

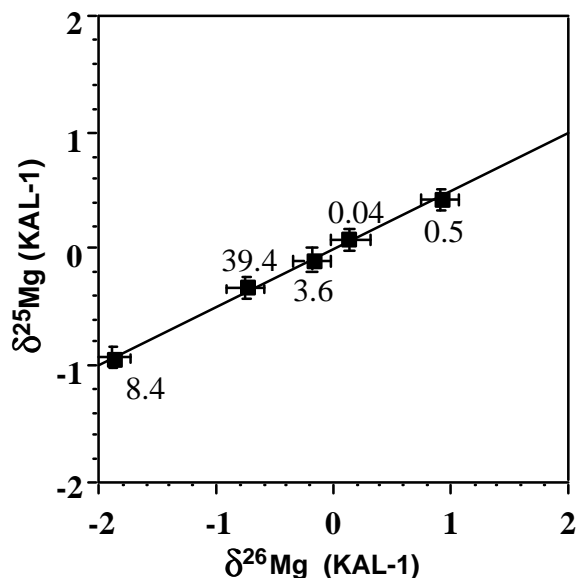
Experimental: Under identical conditions, the degree of evaporative loss should approximately scale with the inverse of the chondrule radius. To search for such an effect, five Tieschitz chondrules of mass 39.4 mg, 8.4 mg, 3.6 mg, 0.5 mg, and 0.04 mg were selected. Roughly 1mg aliquots of the largest 3 chondrules, the entirety of the 2 smaller ones and ~1mg of a komatiite (KAL-1) were heated in 4N HCl. Aliquots of the resulting solutions were diluted in 1cc of high purity water to give concentrations of ~1ppm Mg and analyzed with the Carnegie P54 ICP-MS. Repeated analyses of KAL-1 gave a 1σ reproducibility for $\delta^{25}\text{Mg}=0.09\text{‰}$ and for $\delta^{26}\text{Mg}=0.16\text{‰}$.

Results: The Mg isotopic compositions of the five chondrules, relative to KAL-1, are shown in the Figure, along with their masses in mg. The chondrules' isotopic compositions show a spread of ~3‰ in $\delta^{26}\text{Mg}$ along the mass fractionation line but there is no correlation with size.

Discussion: In an earlier study of 4 Semarkona chondrules, [4] found that all were within error, $\pm 1.5\text{‰}$, of normal. The range of compositions reported here is within these limits. Nevertheless, this range in just five randomly chosen chondrules is somewhat surprising. Limits of $\pm 1\text{--}2\text{‰}$ have been set for isotopic fractionations of K [5] and Fe [6] in UOC chondrules, both of which are much more volatile than Mg. From previous experience, the round chondrules in this Tieschitz disaggregate are mostly excentroradial pyroxene chondrules. The liquidus temperatures of excentroradial chondrules [7] are lower than for the PO/BO chondrules studied by [5,6] and they should have experienced less evaporation. That two chondrules show significant negative fractionation also argues against evaporation. On the other hand, the range is too large for formation of these chondrules by

direct equilibrium condensation or from equilibrium condensates alone.

Numerical simulations imply that, for PH_2 of 10^{-4} – 10^{-3} atm and modest dust/gas enrichments, Fe can be lost from chondrules without producing large isotopic fractionation. This is due to enhanced evaporation rates in the presence of H_2 and exchange with the gas. Both small positive fractionations, due to evaporation, and negative fractionations, due to incomplete isotopic equilibration with the gas during cooling, are possible depending on the conditions. Similar processes may also explain the Mg isotopic compositions.



References: [1] Ebel D. S. and Grossman L. (1997) *LPS XXVIII*, 317–318. [2] Grossman J. N. and Wasson J. T. (1982) *GCA*, 46, 1081–1099. [3] Alexander C. M. O'D. (1996) in *Chondrules and the protoplanetary disk* (R. H. Hewins, R. H. Jones, and E. R. D. Scott, eds.) pp. 233–242. Cambridge Univ. [4] Esat T. M. and Taylor S. R. (1990) *LPS XXI*, 333334. [5] Grossman J. N. et al. (1998) *Meteoritics Planet. Sci.*, this volume. [6] Wang J. and Alexander C. M. O'D. (1997) *Meteoritics Planet. Sci.*, 32 Suppl., A134–A135. [7] Hewins R. H. and Radomsky P. M. (1990) *Meteoritics*, 25, 309–318.

Mn-Mg-Fe AND Mn-Zn CORRELATIONS IN MAGNESIAN CHONDRULES J.S. Delaney¹, C. Schnabel², G. Herzog² and G. Flynn³, ¹Department Geological Sciences, Rutgers University, 610 Taylor Road, Piscataway NJ 08854, USA (jsd@rci.rutgers.edu), ²Department of Chemistry, Rutgers University, 610 Taylor Road, Piscataway NJ 08854, USA (schnabel@rutchem.rutgers.edu), (3) Department of Physics, State University of New York-Plattsburgh, Plattsburgh NY12901, USA.

Introduction: Magnesian chondrules in ordinary chondrites sometimes contain relatively large relict grains of forsterite that predate the formation of the chondrule and may not have been molten during chondrule formation. These olivines differ from those in many other chondrules as they are displaced from the trend of most nebular materials on Fe/Mn vs Fe/Mg plots (1). Olivine (Fo90 - Fo100) with no volatile depletion of Mn (relative to CI chondrites) has Fe/Mn ratios ranging from <15 to 0. [1] The high Fe/Mn of the olivine reflects volatile depletion processes. The moderately volatile Zn is also strongly depleted (<0.1xCI) in chondrules from primitive meteorites but Zn correlations with other elements are poor. We report the relationships between Fe-Mn-Mg and Zn in magnesian chondrules for which the effects of volatile depletion are expected to be strongly developed.

Experimental Methods: Chondrules In ALH 81030,30 (L3.4) were identified petrographically and routine analyses by electron microprobe were used to select targets for high precision Mn (>10ppm), Fe, Ni and Zn (>4 ppm) measurements with the synchrotron X-ray fluorescence microprobe (SXRF) at the National Synchrotron Light Source [2].

Results: Observed Fe/Mn values for forsteritic olivines from seven magnesian chondrules (C1-C7 with PO, BO and granular textures) vary from 35-175 (Figure 1) In contrast pyroxene (En >93) in three chondrules has Fe/Mn <15. Relict olivine grains occur in 3 chondrules and vary from 5% to 80% of the area.

Olivine in each of five chondrules has constant Mn/Mg, and variable Fe. Each olivine has a different Mn/Mg reflecting variable volatile depletion (Figure 1). Depletions range from 0.04xCI to 0.24xCI. Many chondrules, most bulk chondritic meteorites, and pyroxene in three of these chondrules have CI-normalized values close to 1 [1].

Fe zoning in individual olivine grains, shows Fe/Mn - Fe/Mg correlations that cannot be the result of simple crystal liquid fractionation. Kd (Fe/Mn) is normally ~1.0 and predicts constant Fe/Mn with varying Fe/Mg for coexisting olivine and liquid. The olivine zoning follows lines of constant Mn/Mg and therefore reflects Fe exchange between the olivine and its environments. The lowest Mn/Mg ratios are seen in large olivine grains (in C6, C5) that are petrographi-

cally relict (Figure 1) and in the only barred olivine chondrule C4, which may have been totally molten. In C2 the relict olivine is smaller and exchange between it and the host chondrule is more likely.

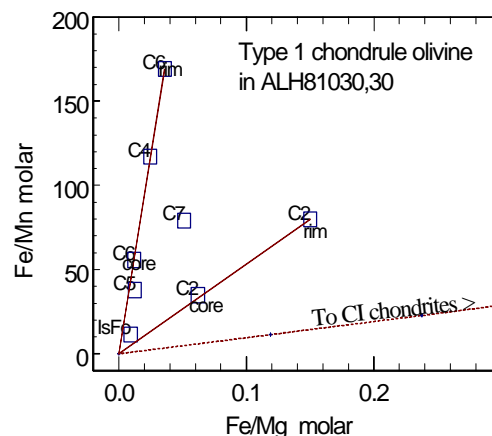


Fig. 1. Fe-Mn-Mg systematics of Mg olivine

The olivine grains have low Zn contents with provisional data ranging from ~30 ppm to the detection limit (< 4ppm). Zn, Fe and Ni are correlated and suggest Zn may be introduced into the olivine by oxidation of a metallic/sulfide precursor. Antarctic weathering provides a potential contaminant but this will be checked in nonAntarctic Type 1 chondrules. Zn abundance appears to anticorrelate with Mn depletion in olivine. Mn/Mg, used as an indicator of volatile depletion, may therefore permit a prediction of the extent of Zn depletion in the same phase. If this can be confirmed in clean olivine then the Mn depletion effect may provide a guideline for the extent of Zn depletion. These objects studied contain so little Zn that they are unlikely to be useful for isotopic studies. The presence of detectable Zn in both the cores of some large olivines and in pyroxene is however, encouraging. If the trends observed are confirmed, they suggest that volatility related variations of Zn and Mn can be identified, and that Type II and III chondrules that also have low Mn/Mg (xCI) may be candidates for Zn depletion and isotopic fractionation studies.

References: [1] Delaney J. (1993) *Meteoritics*, 28, 341. [2] Schnabel et al. (1998) *LPSC XXIX*, Abstract #1738.

OXYGEN ISOTOPIC STUDIES OF ISOLATED AND CHONDRULE OLIVINE FROM RENAZZO AND ALLENDE. L. A. Leshin¹, K. D. McKeegan¹, C. Engrand¹, B. Zanda^{2,3}, M. Bourot-Denise³, and R. H. Hewins²,
¹Department of Earth and Space Sciences, University of California-Los Angeles, Los Angeles CA 90095-1567, USA (laurie@oro.ess.ucla.edu), ²Geological Sciences, Rutgers University, Piscataway NJ 08855-1179, USA, ³Lab. de Minéralogie, Museum of Natural History, 61 rue Buffon, 75005 Paris, France.

The goal of this ongoing study is to combine *in situ* oxygen isotopic analysis with petrographic characterization of olivines in different settings and chondrite groups to investigate nebular processes such as chondrule formation, early chondrule break-up, condensation in the nebula, and mixing of materials between chondrite groups.

We measured O isotopic compositions within individual olivine grains in 5 chondrules from CR Renazzo, 2 chondrules from CV Allende, and 3 isolated olivines from Allende with the UCLA ims1270 ion microprobe using olivine standards with a range of FeO contents to assess matrix effects. These effects were extremely small under our analysis conditions (<2‰ between Fa_0 and Fa_{50}) and only olivines of similar FeO contents were analyzed on the same day.

Two of the analyzed Renazzo chondrules are of type IA: a porphyritic olivine (PO) (Fa_3) and a barred olivine (BO) (Fa_1); the other three are type IIA: two PO (Fa_{16-26} and Fa_{16-32}), and a BO (Fa_{43}). A relict olivine grain ($\sim Fa_3$) in one of the type II PO chondrules was analyzed. The two Allende chondrules are type IA PO (Fa_1 and Fa_3). Two of the three Allende isolated olivines are extremely forsteritic ($Fa_{0.2-0.5}$) and, although their cathodoluminescence has not yet been measured, are probably identical to the blue luminescent olivines sometimes interpreted to represent nebular condensates [e.g., 1,2]. The third isolated olivine has $\sim Fa_3$. Between 3 and 8 different spots were analyzed in each Renazzo chondrule, and two spots were analyzed in each chondrule and isolated grain in Allende.

The olivines define an ^{16}O -mixing trend, however, only the most ^{16}O -rich compositions actually fall on the CCAM line (see Figure). The data define a field similar to that of CV whole chondrules [3], but with a more extended range in isotopic values. The more ^{16}O -depleted olivines actually plot to the left of the fields for whole CV and CR chondrules suggesting that whole chondrule data reflect mixing in the bulk analyses of mafic silicates with mesostasis which has become heavy isotope-enriched through secondary processing. Although based on limited data, it appears that the most ^{16}O -rich forsterites in CVs and CRs are ~ 2 -5‰ less ^{16}O -enriched than forsterites in COs [4] and CIs [5].

Thus far we have observed no significant evidence for isotopic heterogeneity among different grains in a single chondrule with the exception of the relict forsteritic grain within one Renazzo type II chondrule which is ^{16}O -enriched by several ‰ relative to the other olivines in the

chondrule. This homogeneity among the melt-grown olivines argues against oxygen isotopic exchange with nebular gas during chondrule crystallization, previously suggested to be a possible mechanism for explaining the whole CV chondrule trend [6].

Although forsteritic olivines are more likely to be ^{16}O -enriched, we observe no simple correlation of ^{16}O -enrichment with FeO content. This is best illustrated by two examples. First, the two petrographically and chemically similar type I chondrules in Allende show a >5‰ difference in ^{16}O -enrichment. Second, the greatest ^{16}O -enrichment in Renazzo was discovered in a type II chondrule (3 points with Fa_{16-32}).

The three Allende isolated olivine grains have indistinguishable oxygen isotopic compositions from each other and one of the type I chondrules. This argues against a unique origin for the most forsteritic olivines in Allende and other chondrites.

References: [1] Steele I.M. (1986) *GCA*, 50, 1379–1395. [2] Weinbruch S. et al. (1993) *GCA*, 57, 2649–2661. [3] Clayton R.N. et al. (1983) in *Chondrules and Their Origins*, pp. 37-43, Lunar and Planetary Institute. [4] Jones R. H. et al. (1998) *LPSC XXIX*, abstract #1795. [5] Leshin L.A. et al. (1997) *GCA*, 61, 835–845. [6] McSween H.Y. Jr. (1985) *Meteoritics*, 20, 523–539. [7] Weisberg M.K. et al. (1993) *GCA*, 57, 1567–1586.

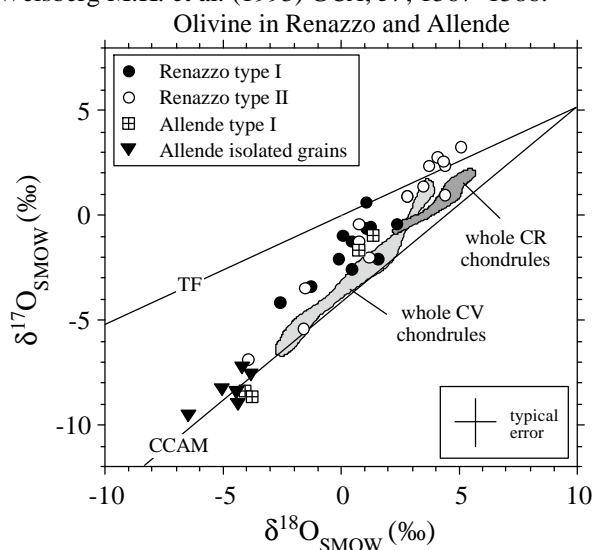


Figure. Three isotope diagram showing single analyses of chondrule and isolated olivines from Allende. Fields for conventional analyses of whole CV and CR chondrules are from [3] and [7], respectively.

METAL-SILICATE DIFFERENTIATION DURING CHONDRULE FORMATION: AN ATEM STUDY.

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Chondrules formed during brief nebular heating episodes, under various temperature and O fugacity (fO_2) conditions. Type I chondrules contain FeO-poor silicates and Fe-Ni metal grains, suggesting that a reduction process occurred, probably during chondrule formation. The metal occurs either as μm -sized blebs within silicate crystals ("dusty olivine") or as larger globules in a silicate melt at olivine grain boundaries [1,2].

In order to better understand the metal-silicate separation during chondrule formation, we conducted an analytical transmission electron microscopy (ATEM) study of type I chondrules from the low petrographic type Bishunpur chondrite (L3.1). The tiny metal blebs within the olivines have low Ni contents (<2 wt%) and are very often surrounded by a silica-rich glass layer (with also some appreciable amount of Al_2O_3 and CaO). This strongly suggests the reduction reaction $\text{Fe}_2\text{SiO}_4 \Rightarrow \text{Fe}(\text{metal}) + \text{SiO}_2(\text{amorphous}) + \text{O}_2(\text{gas})$. Tiny (20-50 nm size) Cr_2O_3 and Ca-phosphates are also present in the silica-rich glass. Cr and P were probably dissolved in the metal at high temperature and low fO_2 , afterward oxidized and exsolved during chondrule cooling.

The metal globules ($>1\mu\text{m}$ size) within the glass (mesostase) at olivine grain boundaries are polycrystalline and contain, both kamacite (2–3 wt% Ni) and taenite (49–52 wt% Ni). They probably result from coalescence of metal extracted from the silicates during a reduction process at high temperature. There is no Ni concentration gradients across the taenite grains, neither plesitic textures, suggesting that the metal assemblage originated from a nonequilibrium crystallization path. The globules contain a number of submicronic Cr-rich or P-rich precipitates which most certainly result from exsolution. These observations are in close agreement with Zanda et al. [3] who suggest that Cr, P, and Si from the silicates were reduced into the metal during chondrule formation. The metallic globules are embedded in a SiO_2 - Al_2O_3 -CaO-rich melt, which also contains some chromite and Ca-phosphate inclusions. At olivine contacts, the melted material frequently recrystallized to form thin Ca-rich pyroxene rims around the olivine grains. The formation of Ca-rich pyroxenes and Ca-phosphates modi-

fied the melt composition (in particular we observe a strong increase of the Al/Ca ratio) in the glass.

Such observations on type I chondrules are compared to the evolution of San Carlos olivine during reduction experiments at high temperature and low (fO_2) [4]. Quite similar textures to natural chondrules are observed at the TEM scale. The olivine interiors contain a high density of submicronic blebs of Fe-rich metal, in close association with a silica-rich glass. However the ratio SiO_2 -glass/metal is low and shows that silica exsolves preferentially at olivine grain boundaries. Mg-Fe zoning at olivine grain boundaries and near the metallic blebs show that the kinetics of the reduction process is governed by the Fe-Mg interdiffusion in olivine.

References: [1] Jones R. H. and Danielson L. R. (1997) *Meteoritics & Planet. Sci.*, 32, 753–760 [2] Rambaldi E. R. and Wasson J. T. (1981) *GCA* 45, 1001–1015 [3] Zanda B. et al. (1994) *Science* 265, 1846–1849 [4] Libourel G. and Chaussidon M. (1995) *Meteoritics*, 30, 536–537.

SIZE DISTRIBUTION OF METAL GRAINS AND CHONDRULES IN ENSTATITE CHONDRITES. D. M. Schneider, D. G. Akridge, and D. W. G. Sears, Cosmochemistry Group, Department of Chemistry and Biochemistry, University of Arkansas, Fayetteville AR 72701, USA.

Introduction: Unmetamorphosed EL chondrites are little studied because they are recent discoveries. Much discussion in the literature compares unmetamorphosed EH with metamorphosed EL chondrites. For instance, Easton [1] reported that EH chondrite metal shows smaller grain sizes than EL metal due to metamorphic coarsening. Previously we reported mineral and textural studies of the chondrules in EL3 chondrites [2,3]. Here we report the metal grain sizes in EL3 chondrites and compare them to EH3 metal grain sizes. The size distribution of both chondrules and metal grains in these meteorites is one of their major features, and we suggest this distribution is related to the fractionation of metal and silicates [4] by gravitational and aerodynamic sorting in a dynamic regolith [5].

Experimental/Results: Metal grain and chondrule sizes in three EH3 (ALH 84170, PCA 91085, and PCA 91238) and three EL3 (ALH 85119, MAC 88180, and PCA 91020) chondrite thin sections were measured using an optical microscope with a calibrated reticle. Only metal grains apparently not associated with sulfides, chondrules, or chondrule rims were measured. The long axis and its perpendicular were measured for each metal grain and each chondrule, and the average diameter determined. Measurements include 199 chondrules and 660 metal grains from the EL3 sections, and 135 chondrules and 491 metal grains from the EH3 sections.

The chondrules and metal grains we measured have a range of sizes, with chondrule diameters of 45–1313 μm in EH and 85–2125 μm in EL, and metal diameters of 8–492 μm for EH and 2–1107 μm for EL. However, the size distribution for metal and chondrules in the EL chondrites are skewed to higher values and the averages are different (Fig. 1).

Discussion: In every sample studied, the average chondrule size exceeded the average size of metal grains. Also, the average size of both the chondrules and the metal in EL chondrites is larger than that of the EH. In Easton's data [1], the EH samples represented a range of metamorphism (types 3–5), while the EL samples were all highly metamorphosed. The EL3 metal data presented here

show the same tendency toward larger grain sizes as the highly metamorphosed EL6 chondrites in Easton's data. Thus the larger metal grain size in EL chondrites is a primary property, and not due to metamorphic coarsening. The EH and EL chondrites show differences in chondrule and metal grain size distributions, with a tendency for both metal and chondrule size to increase from EH to EL. One proposed metal-silicate fractionation model which could explain this difference between the two types is the mobilization of material in a dynamic regolith, as proposed by Sears and Akridge [6].

References: [1] Easton (1983) *Meteoritics*, 18, 19. [2] Schneider et al. (1997) *LPS XXVIII*, 1257. [3] Schneider et al. (1998) *LPS XXVIII*, #1200. [4] Dodd (1976) *EPSL*, 30, 281. [5] Huang et al. (1996) *JGR*, 101, 29373. [6] Sears and Akridge (1998) *Meteoritics and Planet. Sci.*, accepted.

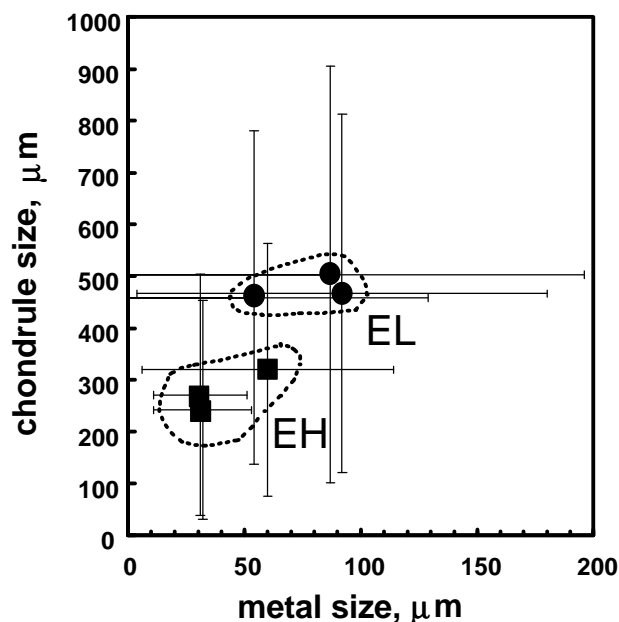


Fig. 1. Chondrule versus metal grain sizes in enstatite chondrites. Error bars are $\pm 1 \sigma$.

GRAIN SIZE AND THE ABUNDANCE OF TROILITE AND MODERATELY VOLATILE ELEMENTS IN LOW-FERRIS OXIDE CHONDRULES IN SEMARKONA. A. E. Rubin¹ and A. L. Sailer^{1,2}, ¹Institute of Geophysics and Planetary Physics, University of California, Los Angeles CA 90095-1567, USA, ²Rockwell Science Center, Thousand Oaks CA 91358, USA.

Recent reports [1–3] suggest that there is an inverse correlation between grain size and the concentrations of moderately volatile elements (MVE: K, Na, Fe, Ni, P, S) among low-FeO chondrules in Semarkona (LL3.0). Troilite is reported absent in low-FeO porphyritic chondrules with a nominal grain size $\geq 25 \mu\text{m}$ [3]. (Nominal grain size is the inverse of the square root of the number of olivine and pyroxene grains per unit area, a parameter which overestimates the true mean grain size [3].)

To determine the origin of troilite in chondrules, we studied 41 low-FeO porphyritic and granular olivine-pyroxene (GOP) chondrules in Semarkona. Troilite is considered primary (i.e., derived from the chondrule precursors) if it is completely embedded in mesostasis or a mafic silicate phenocryst, located within one-half radius ($\frac{1}{2}r$) of the chondrule center and has an apparent igneous texture, e.g., if it occurs as a rind around a metallic Fe-Ni spherule (as in metal-sulfide assemblages in basaltic-andesitic rocks from Disko Island, Greenland [4]). The average olivine and low-Ca pyroxene grain sizes in the low-FeO porphyritic and GOP chondrules are 50 ± 20 and $95 \pm 45 \mu\text{m}$, respectively. Among the 10 chondrules with the coarsest olivine ($\geq 70 \mu\text{m}$) and low-Ca pyroxene ($\geq 150 \mu\text{m}$) grains, 10% are troilite free, 40% contain no troilite within $\frac{1}{2}r$ of the chondrule center, and 50% contain primary troilite. These values are similar to those of the entire set of 41 low-FeO porphyritic and GOP chondrules: 5%, 39%, and 56%, respectively. The 16 chondrules in the set with no unambiguously primary troilite have mean olivine and low-Ca pyroxene sizes (55 ± 15 and $90 \pm 40 \mu\text{m}$, respectively) very similar to the overall averages. The two troilite-free chondrules have mean olivine and pyroxene sizes of 60 and 85 μm , respectively. The 13 highly reduced porphyritic chondrules ($Fa_{\leq 2}$) in the set have olivine and low-Ca pyroxene sizes of 50 ± 15 and $75 \pm 15 \mu\text{m}$, respectively; 62% contain primary troilite. Thus, there is no tendency for troilite to be present or absent in low-FeO chondrules as

a function of mafic silicate grain size or composition.

Hewins [5] stated that the finest-grained low-FeO chondrules were melted to a lesser extent than coarser-grained chondrules; an inverse correlation was found between MVE concentration and mafic silicate grain size [1–3,5]. This implied open-system melting of chondrules because the least-melted, finest-grained objects probably retained their precursor compositions (e.g., CI-level abundances of alkalis), whereas larger, more-melted, chondrules probably devolatilized. However, the high MVE concentrations in fine-grained low-FeO chondrules may not be a primitive composition, but rather a result of parent-body alteration. These chondrules contain troilite, pentlandite, magnetite, awaruite and Fe-carbide [2], essentially the same opaque assemblage attributed by Krot et al. [6] to aqueous alteration. The high alkali concentrations in these objects may result from parent-body alkali metasomatism as in the bleached zones at the margins of cryptocrystalline chondrules in Semarkona and other type-3 OC [7]. There is no evidence that finer-grained low-FeO chondrules inherited high MVE concentrations from their precursor assemblages.

Primary troilite and Na_2O -bearing augite and/or mesostasis occur in most low-FeO chondrules in Semarkona, independent of mafic silicate grain size [8]. These phases indicate very brief heating of chondrules, assuming canonical nebular conditions.

References: [1] Hewins R. H. et al. (1996) *LPS XXVII*, 537–538. [2] Zanda B. et al. (1996) *LPS XXVII*, 485–486. [3] Hewins R. H. et al. (1997) *Ant. Met. Res.*, 10, 275–298. [4] Klöck W. (1986) Ph.D. thesis, Johannes-Gutenberg Univ., Mainz. [5] Hewins R. H. (1996) *Ann. Rev. Earth Planet. Sci.*, 25, 61–83. [6] Krot A. N. et al. (1997) *GCA*, 61, 219–237. [7] Grossman J. N. (1998) *LPS XXIX*, Abstract #1179. [8] Rubin A. E. and Sailer A. L. (1998) *LPS XXIX*, Abstract #1293.

DEBRIS CLOUDS FROM THE EARLIEST PLANETARY IMPACTS: EVIDENCE FROM THE IRISH METEORITE, BOVEDY (L3). I. S. Sanders, Department of Geology, Trinity College, Dublin 2, Ireland.

A role for planetary collisions in the production of chondrules is gradually becoming accepted, even by those who still favour the melting of pre-formed dust balls in the nebula [1,2]. Because chondrule-like objects were definitely produced by impacts on the Moon, albeit in relatively small numbers, [3] argued that meteoritic chondrules probably resulted from impacts between young planetesimals. The reason for the abundance of chondrules in meteorites and their scarcity on the Moon was rather vaguely attributed by [3] to a different collision regime in the very young solar system compared with that on the Moon. What was different? In my view the difference was the temperature of the colliding bodies. Planetesimals in the very young solar system were commonly so hot that they were already internally molten, leaving the kinetic energy of impact only a minor factor in producing melt.

Evidence for early molten planetesimals is compelling. The oldest dates obtained from differentiated (i.e. molten) meteorites, based on both long- and short-lived isotopes, are within a few million years of the start of the solar system. Mutual collisions between planetesimals are clearly documented by, for example, the mixing of silicate and metal in mesosiderites and IIE irons. Also, formation of the extremely old meteorite, Shallowater, evidently involved the collision of a molten planetesimal [4].

What was the nature and fate of the impact ejecta from these dramatic, early collisions? [5] has argued that the resulting ejecta cloud of molten droplets would be a perfect candidate for the transient, local, volatile-rich, 'nebular' environment deemed necessary for the development of chondrules with their retarded-cooling textures.

The Irish chondrite, Bovedy, (L3) contains a variety of objects that help reconstruct an image of an early planetesimal and its post-impact chondrule-rich debris-cloud. Conspicuous multiple (up to 5-stage) compound chondrules [6] suggest a close proximity of spray droplets in the cloud. One porphyritic olivine chondrule measures 1.4×1 cm;

it may be a frozen blob of melt that failed to disperse into spray. In addition to its abundant chondrules, Bovedy contains a variety of interesting objects which are interpreted as fragments of the cooler solid crust or carapace that insulated the molten planetesimal interior. These fragments are of dusty regolith, of earlier generations of now broken chondrules, of coarse-grained peridotite. Chondrule caps attached to some angular rock fragments imply mixing of solid and molten components in the cloud. Such mixing of droplets and dust provides, incidentally, a ready explanation for the so-called relict grains in chondrules. Bovedy also contains pieces of fractionated igneous rock represented by a clast of silica pyroxenite [7], and also by a piece of igneous plagioclase (now plagioclase glass) which contains significant excess ^{26}Mg [mentioned by 1]. One amazing chondrule with immiscibility textures between silica and pyroxenitic glasses may have been derived from the silica pyroxenite rock by impact melting [8]. Some chondrules and rock fragments are coated with progressively finer-grained rims, and they bear a remarkable similarity to terrestrial accretionary lapilli. The coating was presumably added while the objects were lofted in the debris cloud.

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DID JUPITER MAKE CHONDRULES? S. J. Weidenschilling¹ and F. Marzari², ¹Planetary Science Institute, 620 North 6th Avenue, Tucson AZ 85705, USA, ²Dipartimento di Fisica, Università di Padova, 35131 Padova, Italy.

A straightforward interpretation of radioisotopic data suggests that CAIs formed very early in the solar nebula, but chondrule formation began a few My later and continued over an interval of several My [1,2]. Many researchers reject this chronology in favor of early formation of both CAIs and chondrules from different isotopic reservoirs. Reasons for this rejection include: presumed greater availability of energy sources for heating events during formation of the nebula (and lack thereof at later times) [3], and an explicit or implicit assumption that chondrules formed before planetesimals accreted.

Late formation of chondrules would imply that the nebula was relatively quiescent for a few My before a chondrule-forming "cataclysm." Planetesimals would have accreted rapidly during this interval [4], storing CAIs within them. A later event had to break up these planetesimals to produce dust for chondrule precursors, as well as cause heating events that melted them, and allow reaccretion of second-generation planetesimals. We suggest that Jupiter's formation could have supplied a cataclysm of appropriate magnitude and timing. One plausible model for origin of the giant planets is accumulation of a rock/ice core ($>10M_{\oplus}$) over several My, followed by rapid accretion of gas from the residual solar nebula [5]. The forming core would have relatively little effect on the asteroid zone [6], but once Jupiter reached its full mass, its perturbations would affect bodies at the 3:2 and 2:1 commensurability resonances at 3.97 and 3.28 AU. Asteroid-sized planetesimals brought into these resonances by gas drag would be stirred to high eccentricities while their inclinations remained low; frequent collisions would produce large amounts of dust. Resonant planetesimals could attain supersonic speeds, producing shock waves capable of

melting chondrule-sized dust aggregates [7,8]. Additional heating might be supplied by shocks due to density waves excited in the nebula at Jovian resonances [9]. Chondrules and other debris (including CAIs) from disrupted planetesimals would drift inward by gas drag and accrete into second-generation bodies after leaving the resonance region. This process would continue until the nebular gas dissipated from the asteroid zone.

This scenario is broadly consistent with isotopic chronology and cosmogonical models. The age gap between CAIs and chondrules favors slow growth of the giant planets by core-accretion rather than early formation by gravitational instability of the nebula [10]. In this model, chondrite parent bodies are not primitive planetesimals, but were assembled from (possibly multi-generational) debris of earlier-formed bodies.

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THE ABLATION OF SMALL PLANETESIMALS: YET ANOTHER PROBABLE CHONDRULE FORMATION MECHANISM. M. J. Genge, Department of Mineralogy, The Natural History Museum, Cromwell Road, London SW7 5BD, Great Britain (m.genge@nhm.ac.uk).

Introduction: Chondrules are sub-spherical igneous objects found in chondrites and record the thermal and dynamic state of the early solar system. However, no theory of chondrule formation can yet explain the full petrological diversity of chondrules [1]. I describe a new model for chondrule formation in which liquid droplets are produced by the ablation of small planetesimals in nebular shockwaves. This model is particularly significant since it suggests that chondrules may have formed by more than one process.

Ablation of Small Planetesimals: The drag heating of 'large' bodies in a gas medium will lead to the formation of liquid droplets by ablation if relative velocities and gas density are sufficiently large. The formation of droplets by ablation occurs due to the large pressure gradient associated with hydrodynamical bow shocks. These will develop during gas drag for bodies larger than the mean free path of gas molecules which behind nebular shock fronts decreases from ~0.03 to 0.01 m with mach numbers of 4 to 10 (assuming an unshocked ideal H₂ gas with an ambient pressure 1×10^{-5} bars). Bodies larger than a few cm in size will therefore produce small liquid droplets by ablation if they encounter nebular shockwaves. These droplets will cool to form chondrules.

Dust Verses Planetesimals: Dust particles will also melt by gas drag to form liquid droplets and thus may produce chondrules [e.g., 2]. If both dust particles and larger bodies (>3 cm) are present then sufficiently strong nebular shocks would produce chondrules by melting of dust and by the ablation of larger bodies. This illustrates that more than one processes may have been responsible for chondrule formation. The relative abundance of chondrules formed from dust and from small planetesimals will be dependent on the mass distribution of solid bodies and the efficiency of melt production during ablation.

The Nature of Ablation Chondrules: The fusion crusts of the chondrites provide an appropriate analogue to the ablation products of planetesimals. They suggest that ablation melts will have compositions similar to whole rock but with depletions in the si-

derophile and chalcophile elements [3] due to the separation of sulphide and metal liquids. The large mass to surface area ratios of ablation melts (at peak temperature, prior to separation) reduces volatile element losses by evaporation resulting in high Na and K abundances [3]. These characteristics are broadly similar to chondrules some of which might therefore have formed by ablation [4].

Once ablation droplets have separated they will behave identically to droplets formed by melting of dust particles. Post shock phenomena which successfully explain many of the petrological features of chondrules (including chondrule rims) as discussed by Connolly and Love [2] thus also apply to ablation chondrules.

Conclusions: Unless the total mass of small planetesimals was significantly larger than that of dust particles during chondrule formation, then most chondrules probably did not form as ablation spheres. However, if chondrules did form by drag heating then some chondrules will have originated by ablation. Other mechanisms which are also capable of producing liquid droplets in the early solar system (e.g., impact melt droplets) may also have contributed to the chondrule population. If chondrules did form by a number of processes then no single model will be able to explain their petrological variation.

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THE LACK OF POTASSIUM ISOTOPIC FRACTIONATION IN BISHUNPUR CHONDRULES. J. N. Grossman¹, C. M. O'D. Alexander², J. Wang², B. Zanda^{3,4}, M. Bourot-Denise⁴, R.H. Hewins³ and Y. Yu³. ¹U.S. Geological Survey, Reston, VA 20192. ²DTM, Carnegie Institution of Washington, Washington DC, 20015. ³Department of Geological Sciences, Rutgers University, Piscataway, NJ 08854. ⁴Museum National d'Histoire Naturelle, 61 Rue Buffon, 7500 Paris, France.

Background: Volatile elements can provide some of the best constraints on the nature of the chondrule formation process and of chondrule precursors. Volatile-poor chondrules may have formed either from volatile-poor material, or by partial evaporation of volatile-rich material during melting. Volatiles may also have been affected by secondary processes, such as parent-body (aqueous) alteration of chondrules.

Rayleigh-type evaporative loss of K from synthetic chondrules produces rapid increases in $\delta^{41}\text{K}$, even at modest levels of evaporation [1]. In [1], the mesostasis in three low-FeO chondrules were analyzed, and none showed any resolvable ($<2\%$) fractionation of K isotopes. [1] assumed that entry of K into the chondrules after accretion was minimal and, therefore, that evaporative loss of K did take place, but probably in a dust-enriched environment, allowing isotopic exchange between gas and melt.

New studies: Here, we attempt to rule out that secondary entry of volatiles into chondrules erased evidence of primary K isotopic fractionation. We identified inclusions of glass inside olivine crystals in 6 Bishunpur chondrules. As in Semarkona [2], several of these inclusions have extremely low Na/Al ratios compared to their chondrule mesostasis. There is evidence that volatiles, including K, did enter certain chondrules after solidification, probably during aqueous alteration [3]. The glass inclusions, especially alkali-poor ones, offer the best hope of finding material that escaped any such alteration. These inclusions, as well as normal chondrule mesostasis were analyzed by ion probe as described in [1].

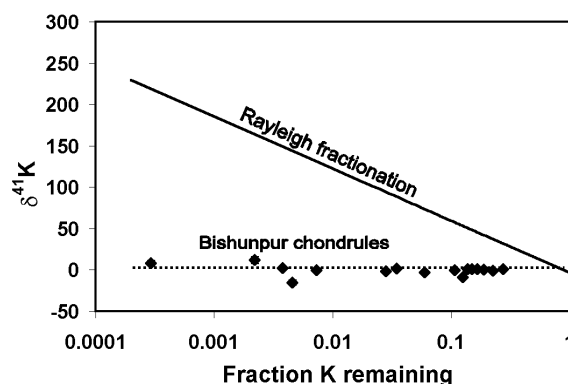
Results: Five of the chondrules were type I (olivine, Fa_{0-1}), with mesostasis Na_2O contents of 0.2 to 9 wt% (the latter being an unusual type I chondrule). The sixth chondrule had Fa_9 olivine and mesostasis with 2-4 wt% Na_2O . One type I chondrule and the sixth chondrule had glass inclusions that were significantly lower in alkalis than surrounding mesostasis.

The analysis of 17 areas of mesostasis and glass inclusions are plotted in the Figure. The fraction of K remaining assumes initial L-chondrite-like K/Al ratios for all the chondrules. None showed any significant K isotopic fractionation, confirming the results in [1].

Discussion: From the analyses, it seems likely that Bishunpur chondrules lacked any K isotopic fractionation even before parent body alteration occurred.

This is consistent with direct condensation models of chondrule liquids [4], although we doubt that such models can explain many of the properties of real chondrules (e.g., relict grains, fast cooling rates). Type I chondrules could have formed from volatile-poor material such as high-temperature condensates, which would not be expected to show K isotopic fractionation, although the correlation of chondrule grain size with volatile content may argue against this [5] depending on the effect of secondary alteration. If type I chondrules did experience evaporative loss of volatiles, then the combined effects of enhanced evaporation rates due to fairly high P_{H_2} and exchange with the surrounding gas while molten must have reduced the amount of isotopic fractionation in chondrules to levels we are unable to detect. This does not require that volatiles recondensed into chondrules to any great extent during cooling: they were simply able to exchange with the melt. Indeed, the zoning profiles of glass in many type I chondrules requires that most observed secondary entry of volatiles happened after solidification and incorporation into a parent body.

What is now certain, however, is that chondrules did not experience simple Rayleigh-type loss of volatiles.

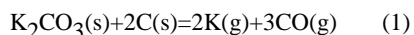


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INCORPORATION OF POTASSIUM IN MOLTEN SYNTHETIC CHONDRULES UNDER CONTROLLED POTASSIUM AND OXYGEN PARTIAL PRESSURES. P. Georges, G. Libourel and E. Deloule, CRPG-CNRS, UPR 9046, BP 20, 54501 Vandoeuvre les Nancy cedex, France (pgeorges@crpg.cnrs-nancy.fr, libou@crpg.cnrs-nancy.fr, deloule@crpg.cnrs-nancy.fr).

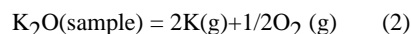
Introduction: Due to the high volatility of alkalis at high temperature and low O fugacity, chondrules of unequilibrated ordinary chondrites (UOC) are generally interpreted as the result of brief heating events (flash heating) occurring in the pristine solar nebula. This is shown by alkali loss experiments from melts [1–2] where transient heating are able to reasonably reproduce the alkali contents observed in type I and type II chondrules, suggesting heating times in a range of few seconds to few minutes. However, such a scenario doesn't take into account the effect of partial pressure of alkalis during chondrule formation, which may affect the rate of retention and/or volatilization of alkalis and in turn, our interpretation of chondrule forming events, i.e. chondrules precursors and heating-cooling conditions. To test the hypothesis of whether an alkali-rich vapor would affect alkali volatilization and back-diffusion in chondrules, new experiments were designed in order to control partial pressure of alkalis at high temperature under controlled O fugacity and one bar total pressure.

Experimental: Since K(g) is the predominant potassic gas species under reduced conditions, a mixture of K₂CO₃ and graphite, located in the low temperature zone (at around 1000°C) of a vertical furnace, is used to establish a partial pressure of K according to the following reaction:



The K gas is carried to samples: K-free or K-bearing silicate melts, situated in the high temperature zone of the furnace (1000-1700°C) by a flow of gas of imposed PO₂ (CO-CO₂-Ar). The partial pressure of K, i.e. PK, is determined by thermogravimetry and related to mass loss ($\Delta m/\text{dt}$), temperature and flow rate of vector gas. Samples, suspended on an independent alumina rod, are drop-quenched at

different times during the experiment (multi-quench system) and analyzed by electron microprobe. At these high temperature conditions, volatilization or condensation of potassium in molten silicates can be therefore described by the following reaction:



Results: At equilibrium, simultaneous control of PK and PO₂ allows calculation of the K₂O activity in agreement with this equation :

$$a_{\text{K}_2\text{O}} = ((\text{PK})^2 \cdot (\text{PO}_2)^{1/2}) / K_{eq}(2)$$

This protocol was tested on a K-free silicate melt sample (36 wt% SiO₂, 12 wt% Al₂O₃, 46 wt% CaO and 6 wt% MgO) at 1450°C under various oxygen fugacities. Results show that the transfert of K(g) from source to samples is possible. At equilibrium, potassium solubility in the melt is clearly dependent on both PO₂ and PK, as predicted by equation (2).

Using chondrule-like composition and samples quenched at different times, we will show that this protocol allows i) quantification of the kinetics of K(g) condensation in the melt phase or the volatilization rate of K₂O (melt) into the gas phase, under known PK and conditions close to chondrule formation environment, and ii) the establishment of some constraints on the time scale of chondrule formation events, assuming that Na and K behave in a similar way.

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OXYGEN ISOTOPE RATIOS OF NATURAL AND SYNTHETIC CHONDRULES: EVIDENCE FOR IN SITU REDUCTION BY CARBON. R. D. Ash^{1,2,3}, H. C. Connolly Jr.⁴, C. M. O'D. Alexander³, G. J. MacPherson² and D. Rumble III¹, ¹Geophysical Laboratory, Carnegie Institution, 5251 Broad Branch Road NW, Washington DC 20015, ²Department of Mineral Sciences, MRC NHB-119, Smithsonian Institution, Washington DC 20560, ³Department of Terrestrial Magnetism, Carnegie Institution, 5241 Broad Branch Road NW, Washington DC 20015, ⁴CalTech, MC 100-23, Pasadena CA 91125 (ash@gl.ciw.edu).

Introduction: Experiments show that the characteristics of natural Type IA chondrules (both silicate and metal chemistry) are reproduced by the incorporation of a reduced carbon phase into the starting materials [1]. During heating the C is oxidised and lost as CO or CO₂, scavenging oxygen from the silicates thereby producing metallic Fe [1]. Fractionation factors indicate that the production of CO/CO₂ by olivine reduction should result in a mass dependent enrichment of the residue (i.e. chondrule) in the light O isotopes [2].

Herein we present O isotopic analyses of synthetic reduced chondrules to further test this C reduction model for Type IA chondrule formation. These data are then compared with the observations of a natural Type IA chondrule from Tieschitz.

Experimental: Four experimental charges were prepared; two with Type IA and two with Type IIA analogue compositions; 5 wt% graphite was added to one charge of each composition. These were then flash melted under identical conditions, at 1725°C and an fO₂ of -1.5 log units below IW maintained by a CO-CO₂ gas mixture. The resultant charges were petrologically characterised and analysed for O isotopes using the Carnegie Institution UV laser fluorination technique [3, 4]

Results: Oxygen isotopic fractionations were measured between both experimental pairs. Type IA and Type IIA analogue charges without graphite gave $\delta^{18}\text{O}$ values of +6.50‰ and +7.48‰, the corresponding charges with C gave $\delta^{18}\text{O}$ values of +5.62‰ and +6.32‰ respectively. As predicted, the presence of reduced carbon in the synthetic charge precursors leads to residues with lighter oxygen isotopic compositions, by 0.88‰ and 1.16‰.

Discussion: Chemically reduced chondrules have been used to infer the O fugacity and, hence, the dust/gas ratio of the solar nebula in which they are assumed to have formed [5,6]. However the analyses herein indicate that the mineral chemistry of chondrules may be profoundly affected by cosmochemically reasonable amounts of reduced, probably organic, C in natural chondrule precursors.

Comparison with a Natural Reduced Chondrule: Oxygen isotopic analyses of 25 ferromagnesian chondrules from Tieschitz show that 17 of them lie on a slope 1 line [7], which is indistinguishable from the Equilibrated Chondrite Line (ECL - [2]). These are interpreted as

pristine isotopic compositions produced by the mixing of two components. A further seven, altered, chondrules lie toward more ¹⁸O-rich compositions—to the right of this line on a three isotope plot; possibly due to parent body interactions between the chondrules and a fluid phase. One chondrule, however, lay toward lighter compositions, i.e. to the left of the ECL. This chondrule is a highly reduced Type IA chondrule, Fo_{99.2-99.4} with metal containing dissolved Si and Cr. Assuming the initial O isotope composition of this chondrule precursor also lay on the ECL, we calculate a fractionation of 1.3‰ accompanied the reduction—close to that observed in the synthetic analogues.

Thus far this is the only well characterized OC chondrule with Fo>99 for which oxygen isotope ratios have been determined. One chondrule, from Bjurböle, has shown similar unusually light O but was not petrographically characterized [2]. The deviation from the ECL of this Bjurböle chondrule is the same as that of the Tieschitz chondrule. The lack of O isotope analyses of such chondrules may be due to their smaller size compared with "normal" chondrules [8], making isotopic analysis difficult. Alternatively it may reflect the paucity of these highly reduced chondrules.

Conclusions: We have shown that the incorporation of reduced C in synthetic chondrule analogue precursors leads to lighter O isotopes in the resultant chondrule.

The only O isotopic analysis of a known, highly reduced, UOC chondrule shows that it too has a uniquely light O isotopic composition. This observation demonstrates the importance of C in the formation of reduced chondrules.

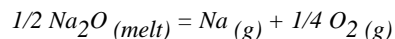
References: [1] Connolly et al. (1994) *Nature*, 371, 136. [2] Clayton et al. (1991) *GCA*, 55, 2317. [3] Rumble et al. (1997) *GCA*, 61, 4229–4234. [4] Rumble et al. (1997) *M.A.P.S.*, 32, A111. [5] Johnson (1986) *GCA*, 50, 1497. [6] Grossman (1988) in *Meteorites and the Early Solar System* (Kerridge & Matthews, eds.), p. 680. [7] Ash et al. (1998) *LPS XXIX*. [8] Jones and Scott (1988) *LPSC XIX*, 565.

Introduction: Chondrules of unequilibrated ordinary chondrites show variations in moderately volatile element contents. It has been demonstrated that these concentrations are clearly affected by the thermal history of these objects. However, the behavior of Na and other alkalis is still poorly known at high temperature and reducing conditions. Thus, the goal of this study is to determine the volatility of Li, Na, K and B under a wide range of experimental conditions, some of which approaching the supposed environment of chondrule formation.

Experimental: Experiments were, at first, focused on volatilization of Na from silicate melts using the Pt wire-loop method. The spheres were about 3 mm in diameter corresponding to 35–40 mg of sample. All experiments were performed in a vertical furnace, at atmospheric pressure and in the temperature range from 1400° to 1600°C. The oxidation conditions were controlled with a CO/CO₂ gas mixture using mass flow meters, and varied from CO₂ to pure CO, corresponding to fO₂ between 10^{-2.5} to 10⁻¹⁴ atm. Two sets of experiments were performed using total flow rates of 300 cc/mn and 900 cc/mn. Run duration varied from 1 min to 2 days after which samples were rapidly quenched in the furnace atmosphere (e.g. cooling gradient of about 400°–500°C/s). Glass spheres were polished and analyzed using Cameca SX 50 electron microprobe.

Results: The absence of concentration gradient in the spheres implies that volatilization of Na at the surface rather than diffusion of the Na-bearing species within the melt is the rate limiting mechanism. At fixed oxygen fugacity,

thermal activation energies of Na-loss were calculated and are in good agreement with data from the literature [1]. However, this study shows that under high temperature and/or reducing conditions, the gas flow rate is a critical parameter for the characterization of Na volatilization rates. This is mainly due to the existence of a competition between surface vaporization and re-incorporation of sodium from the gas surrounding the sample. Nevertheless, with high enough flow rates, Na loss can be accounted for by the following reaction:



in agreement with previous work [1]. However, below IW buffer, our volatilization data indicate a weaker oxygen fugacity dependency.

The same kind of experimental procedure has been used to compare the volatilization of other alkalis like Li or K and of B, Li and B content being analyzed using the CRPG-CNRS ion-microprobe Cameca IMS-3f. Boron and lithium are found to be much more volatile than Na in air, whereas the volatility of K and Na are similar. Moreover, thermodynamic calculations also predict different behavior of Na, K and Li, B vaporization rates as function of oxygen fugacity, due to differences of volatilized species: Na (g), K (g), Li (g), LiO (g) and B₂O₃ (g).

References: [1]_Tsuchiyama A., Nagahara H., and Kushiro I. (1981) *GCA*, 45, 1357–1367.

PRE-EXPOSURE TO COSMIC RAYS OF CHONDRULES. E. Polnau¹, O. Eugster¹, U. Krähenbühl², and K. Marti³, ¹Physikalisches Institut, University of Bern, CH-3012 Bern, Switzerland, ²Department of Chemistry, University of Bern, CH-3012 Bern, Switzerland, ³University of California at San Diego, La Jolla CA 92093-0317, USA.

As part of our continuing investigation of a possible chondrule pre-exposure to cosmic irradiation relative to that of matrix material we present results on the chondrites Sena, Kress, Grassland and Bjurbole. The exposure ages of all measured samples show longer exposure for the chondrules than for the matrix of each meteorite (Table). This confirms our earlier results [1] and can be explained by a pre-exposure of the chondrules in the solar nebula before they were accreted into the meteorite parent material.

Cosmic-ray exposure ages (Ma):

		T ₃	T ₂₁	T ₃₈	T _{av}			
Sena	m. #7	1.02	1.00	1.36	1.13			
(H4)	ch. #2	1.43	1.15	1.76	1.45			
	ch. #4	1.29	1.28	1) ¹⁾	1.29			
Kress	m.	33.9	31.2	2) ²⁾	32.6			
(L6)	ch.	37.8	32.4	2) ²⁾	35.1			
Grassland	m.	8.24	9.35	2) ²⁾	8.80			
(LL4)	ch.	9.13	9.75	9.52	9.47			
		T ₃	T ₂₁	T ₃₈	T ₇₈	T ₈₃	T ₁₂₆	T ₈₁
Bjurbole ³⁾	m.	8.4	9.0	7.9	8.3	8.7	7.4	15.0
(LL4)	ch.	9.2	10.4	8.3	8.4	9.6	11.5	17.4

m: matrix, ch: chondrule(s)

¹⁾ large trapped Argon correction

²⁾ ³⁸Ar loss due to weathering

³⁾ apparent ages, see text

Alternative explanations are preferential gas loss of the matrix material compared to the chondrules or a bias in the adopted production rates. Therefore, we applied the ⁸¹Kr-Kr dating method to Bjurbole, since (i) it does not require the assumptions on target element chemistry and on shielding dependence of the

production rate, (ii) is not affected by gas loss and (iii) has an abundance of chondrules. The data show that all methods yield consistently higher ages for the chondrules relative to the matrix and are best explained by a pre-irradiation of chondrules. However, the ⁸¹Kr-Kr ages require also another explanation, since they are higher than the ages based on stable isotopes. The measured ⁸¹Kr concentration of 0.0169×10⁻¹² cm³STP/g correspond to a (²²Ne/²¹Ne)_c of 1.27 [2, Fig.10], whereas the measured (²²Ne/²¹Ne)_c is 1.084. This indicates a two stage exposure for the Bjurbole meteoroid after break-off from its parent body. The noble gas data for the matrix sample, coupled to the chemical composition (4.9 ppm Rb, 14.3 ppm Sr, 2.1 ppm Y, and 7.2 ppm Zr) are consistent with a first stage lasting 6.0 Ma and a second one of 2.3 Ma. Furthermore, for Bjurbole chondrules within the meteoroid we calculate a pre-exposure before accretion of 1.3 Ma.

The Bjurbole data show that longer exposure ages of chondrules can not be due to preferential gas loss of the matrix or bias in production rates. We obtain the following pre-exposure times of chondrules (2σ errors): Sena#2 - 0.32 ± 0.17 Ma, Sena#4 - 0.28 ± 0.13 Ma, Kress - 2.6 ± 1.4 Ma, Grassland - 0.64 ± 0.25 Ma, Bjurbole - 1.3 ± 0.8 Ma.

Acknowledgments: This work was supported by the Swiss NSF.

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